MICROELECTRONICS

By

Charles Husson
NASA Langley Research Center

[redacted]

22182

ABSTRACT

Out of the potpourri of technologies used to obtain microminiature circuits has evolved a discipline called microelectronics. Photolithography and the chemical and physical processes in materials are united to provide building blocks of electronic systems which are extremely small and reliable. Microelectronics enables a direct, rapid, and effective solution to many of the problems of present-day science including not only those of electronic and aerospace disciplines, but to an increasing degree, those of biology and the medical sciences.

author

[redacted]

MICROELECTRONICS

The general field of microelectronics, by virtue of its newness and challenge, has been written on extensively and in detail. This article, therefore, I will direct at the underlying principle and philosophy and, more importantly, at some of the ultimate potentials which its techniques can accomplish rather than to add to the voluminous documentation of detailed procedures. I should like to introduce the article in this light with an excerpt from the pages of Von Hippel's "Molecular Science and Molecular Engineering"[1]

> "Fundamental Science - - - has reached the stage where a more powerful approach [to electronics] becomes possible"
> "Molecular Engineering," the building of materials to order - - - the time of synthesis has arrived, in which we begin to think about the fundamental properties of matter and their application in unified vision,"

I would especially like to call attention in the beginning to the importance of the technique of synthesis in building systems to accomplish desired objectives. Microelectronic and molecular engineering, which I shall use almost interchangeably in the following because of their exceedingly close relationship, are beginning to provide building blocks that enable the direct, rapid, and effective solution of many of the problems of present-day science including not only those of electronics and aerospace disciplines, but to an increasing degree, those of biology and medical sciences. This comes about by virtue of the fact that most desired performance objectives such as the determination of the way in which a man's or other animal's body reacts to its environment are accomplished through the performance in sequence, however complex, of certain basic and usually simple functions. In a good many cases these functions are as simple as determining that something is or is not: thus, a heart beats or it does not; a spacecraft is above a certain temperature or it is not; a certain time has been exceeded or it has not.

This is-or-is-not function, of course, has become almost the fundamental basis of the computer industry. Other simple functions, amplification, detection, modulation, and likewise simple signal conditioners, are the building blocks of many technologies to accomplish an overall function which is frequently described as data acquisition. Data, of course, is the accumulation of knowledge from which a scientist is able to draw conclusions in the light of his knowledge and experience and enables progress.

I shall outline in the following, first, the history and background of the microelectronic discipline in a chronological order giving a few representative examples of the types of equipment that are currently in use and a critique on potentialities and sprinkle throughout the discussion what I believe are the significant objectives to which the field may aspire in a philosophical sense.

Background

The word microelectronics, first coined by the Diamond Ordnance Fuze Laboratories[2] (DOFL) of Washington, D.C., has become generic and refers virtually to all concepts of microminiaturization. Those who first directed their efforts to microminiaturization to achieve small size and later reliability were members of a National Bureau of Standards research group which evolved into DOFL. A proximity fuse for artillery weapons was the focal point of these efforts. Subsequently, the emphasis on reliable performance of microminiature electronic fuses led to microelectronics. Reliability, then, is one of the central factors of microelectronics. Of course, the search for reliability is not unique to spacecraft; medical electronics, the mass production industries, and the military also demand reliable performance from electronic systems.

Reliability implies a predictability as to the probable life, not the ad infinitum performance of a system - a condition not readily met without a basic knowledge of the physical and chemical properties of electronic devices. Simple electronic devices can be deceptive. I can recall my own experiences in attempting to assess the reliability of gas thyratrons - simple three electrode controlled gas discharge tubes where electrical excitation of one electrode triggered a discharge between the other two. These were common welding process control devices in wide use in the automotive industry and a predictable end of life would be advantageous to users as it would allow an orderly preventive maintenance program rather than experience costly malfunctions on mass production lines. I learned from this experience that the gaseous electrical discharge is one of nature's most complex phenomena, understood only empirically. Reliability can only be accurately predicted with scientific facts and not by the probative theory of empiricism. This particularly applies to thermionic emission, upon which the vacuum tube depends for proper functioning. Electronic systems consistently yielded reliability to the vagaries of the vacuum tube, for vacuum tube technology, especially thermionic emission at best is not completely understood. Regardless of the skill of the designer, the life and aging characteristics of the thermionic cathode always cast a shadow of doubt on the reliability of performance.

The physics of gas discharges, thermionic emission, conductivity in carbon resistors, and all the electrical processes of electronic systems had to be determined more accurately; the only alternative, of course, was to seek new material phenomenon which were predictable and applicable to electronics systems. Curiously enough, it was during one of the fundamental studies to seek a better understanding of dielectric materials, that solid state electronic devices were discovered which were to be the successful replacements of the gas and vacuum tube. For out of the basic studies of Brattain and Bardeen[3] in 1948 came the transistor, and shortly thereafter Shockley[4] developed a P-N junction theory, predicting junction transistor action, and designed the classical "paper transistor." Shockley's theory made it possible to quantitatively check theory in terms of the basic semiconducting properties of a junction. Here was a device based on a physical phenomenon which was understood and predictable. Within 15 years transistors became the mainstay of electronics, and monocrystalline valence semiconductor theory the foundation of microelectronics. Thus the problem was solved by revolution rather than evolution and it is bypasses in technology such as this that produce real progress.

Reliability and miniaturization problems, however, were not solved by P-N junction theory alone. Processing technology is not automatically advanced with each newly discovered material phenomenon, hence, early transistors were not reproducible in quality and performance. Regardless of the skill of the designer, circuits had to be individually trimmed for proper operation. Other components in the electronic system such as resistors and capacitors suffered from the same constraint: thus, components were selected out of large production lots and graded to a specification. Obviously, the fundamental physical and chemical processes were not understood - a condition detrimental to the requirements of enhanced reliability. In view of this, one can outline in simplified form two basic guidelines for the processing of reliable systems: The electronic system, building block, or component must be processed by reproducible techniques whose quality could be described statistically; they must operate within the concepts of understood physical or chemical processes. Of all the processing techniques attempted, selected microelectronic technologies appear to best satisfy these basic guidelines. Technologies developed out of associated microelectronics research are approaching a higher reliability, a reliability which apparently could not be achieved with discrete component and wiring techniques.

The next thing to be noted is the implementation of this "paper technology" into usable electronic functions or building blocks. In contrast to previous fabrication techniques, microelectronics demand exacting circuit design. In view of the investment of time and materials, this should not be difficult to accept. Mass production techniques, however, are applicable to microelectronic disciplines and final costs for quality systems are actually lower than for equivalent discrete electronic functions.

Illustrated in figure 1 are the various approaches to microelectronics. For comparison, two circuits, which I shall call conventional, are also shown. Each circuit is identical in function only and performs an "is" and an "is-not" function or more commonly, a flip-flop or binary counter. Note that the printed circuit board flip-flop is similar to the adjacent thick film circuit. It is, in fact, a one-for-one correspondence as each component occupies the same general location and is easily identifiable. Component identification will become increasingly difficult as other disciplines are discussed.

The thick film circuit shown here in figure 1(b) is fabricated by a variation of the silk screen printing technique; a stainless-steel precision screen replaces the silk and electroceramic materials replace the dyes. Conductors, resistors, and capacitors are fabricated by the screen circuit technique on a ceramic substrate. Transistors and diodes are attached as discrete components as a compatible process for active device fabrication has not been developed. In the thick film circuit, bulk properties of materials are utilized. A thick film may be defined as a thickness at least ten times greater than the mean free path of an electron in that material. "Thin film" has been loosely employed to describe any film deposited by evaporation, sputtering, or pyrolytic processes, but strictly speaking a thin film has a thickness on the order of the mean free path of an electron in that material.

Figure 1(c) is an evaporated thin film circuit formed on a substrate of glass or polished alumina. Some resistors are thin films as they utilize the surface properties more than the bulk properties to achieve higher resistivities than the elemental material. The conductors are thick films and the capacitors are usually conventional sandwiched dielectrics, with thick film electrodes and silicon oxide dielectrics. Active devices are usually attached separately as with the thick film screen circuit. Inductors in both disciplines are either attached separately or if the inductance is sufficiently low, a metallic spiral inductor may be deposited on the substrate. Some thin film active devices are being investigated, but none has proved commercially successful.

The fourth illustration in figure 1(d) is an integrated circuit. It has relied heavily on transistor fabrication technology for its success. Active devices, capacitors, resistors, and some very low inductances are formed within the substrate. In the previous disciplines the substrate served only as a structural skeleton to support the components. On the other hand, integrated circuits utilize the basic physical properties of the substrate, a monocrystalline semiconductor, the properties of which can be locally modified by the diffusion of impurities into the lattice structure. Current carrier mobility is thus modified and the current carrier mechanism, hole or electron, selected.

Discrete areas of the small silicon crystal substate are isolated by one of several means,[5] and, in each area, devices are formed by planar diffusion. Planar formation of components can be defined as a two-dimensional fabrication technique where thin film impurity centers are locally diffused into a crystalline surface. Triply diffused concentric layers at varying impurity concentrations and depths form the atom spaced phase boundaries necessary for transistor action. Here, as in other microelectronic techniques, precise location of junctions and dimensional control of the diffused surface area is critical. Variations of impurity dopant and concentration may be used to form resistors, transistors, and diodes. Hence simultaneous and sequential formation of devices is possible by the same basic process. The devices are interconnected by an evaporated metal film pattern.

The thick film, thin film, and integrated circuits are available in many forms and variations each dictated by the basic limitations of each technology. At times and with sacrifices in reliability, the best feature of each of these is used to great advantage to form a hybrid technology. Economics, electrical characteristics, and application serve as constraints on each variation or form. The chart in table 1 shows some of these constraints. The thin films do not show a great advantage in any area except potential resistance to radiation damage. The advantages of one technology over the other are more readily apparent when one considers the process, materials, and applications.

The disciplines I have just discussed may be considered as commercial microelectronics. There are two other basic concepts in the developmental stage which merit comment: Molecular electronics and electron-beam machine thin films.

Stroull[6] in 1958 developed a molecular circuit where the bulk properties of P-N junctions in a silicon crystal were employed to form a light detector. Basically a light energy-dependent variable-frequency oscillator, it was the first announced semiconductor integrated circuit. It was also truly molecular, in that the smallest part still retained the general properties of the whole. The commercial success of the more discrete diffused monolithic integrated circuits deemphasized the molecular approach, but research and development are continuing. Stroull has said that it is only a matter of time before renewed efforts in this area will yield a wide variety of functions. However, the ground work had been laid for the monolithic semiconductor integrated circuit, a technology more related to the thin film than the molecular circuit.

Shoulders[7] in 1960 at the Stanford Research Institute published a report describing electron beam micromachining techniques and their application to microelectronics. Virtually all existing microelectronic fabrication methods are based on light optics and hence are diffraction limited. Electron optics is required to resolve dimensions less than 1 micron and Shoulders has developed techniques to form micron-sized components. A thin metallic film is evaporated on a substrate and coated with a thin organic resist film which can be polymerized by electron beams. A silicon alcohol, triphenylsilanal, is preferred because the unpolymerized surface will evaporate readily and when heated may be removed by the vacuum system. A silica pattern remains and serves as an etchant mask. By these means, he has succeeded in obtaining better than 200 angstrom line resolution. Utmost purity and a very high vacuum, 10^{-12} torr, are required to obtain these resolutions. Chlorides and fluorides make excellent etchants as their byproducts are easily removed under vacuum. With these techniques, Shoulders has made field emission devices. He does not intend to use P-N junction semiconductor phenomenon as his devices will rely heavily on Townsend gas discharges, Esaki electron tunneling, field emission, and photoconductive effects. One of the primary applications of Shoulder's effort is the learning machine.[8] Micron-sized components will serve as active devices and adaptive weights memories for large-scale learning machines and adaptive mechanisms. By 1970, under sponsorship of the Office of Naval Research and the Electronics Research and Development Laboratories, Fort Monmouth, New Jersey, systems are expected to be in operation with very small multimillion bit memories and self-organizing systems.

Photolithography

The fabrication of any microelectronic structure demands precise reproduction of the form factors which define the electrical characteristics of the components. Resistors and capacitors are defined by the length, width, thickness, and nature of the material; transistor and diode characteristics are defined by atom spaced "boundaries" within a semiconductor crystal. Obviously, this exceeds the diffraction limit of light optics. The reproduction of complex patterns with line widths and spacing less than 5 microns is required to implement microelectronics. This is not an easy problem as the multitude of processing steps and materials employed must meet stringent requirements of purity, passivity, and accuracy.

It is fortunate that commercial photolithography provided us with a number of materials and processes which were useful in early microelectronic techniques. Some of the materials are photo-resists[9] and conductive ceramic inks;[10] the processes include screen printing and etched photo plates. Each of these has been improved by several orders of magnitude due to the demands of new electronic technologies. Photo-resists, particularly, have been improved to produce 0.3 to 5 micron lines, resist acids, and alkalis and react to light or electron beams. Photo-resist is an organic, insulating liquid deposited as a thin film surface coating on a substrate. Light or electrons polymerize exposed surfaces, allowing the unexposed surface to be washed completely away by the developer which may be water, trichlorethylene, or other organic solvents. The "resists" may be positives, thereby reversing the process. This resist pattern may be used in one of two ways: a printing mask when reproduced on a fine mesh screen, or an insulation mask for the selective etching, oxidation, or electroplating of a material when reproduced on that material. The selective etching-through of a thin material provides a mask for evaporating or sputtering patterns on substrates. Of course, when one seeks accuracy at 5 to 10 microns, scaling of patterns is implied. Photoreductions at 500X are not unusual. Large-scale masks for reduction are usually machine cut or computer programed and automatically cut into the opaque side of a translucent/opaque dimensionally stable plastic sandwich. The opaque material is removed and back illumination of the mask yields a negative pattern.

It is obvious that in microelectronics, one is dealing with biological dimensions. However, this is not particularly new as transistor technology has required dimensional control to better than 1 micron for several years. This was achieved by machining processes, either gas or liquid etch, or metal-to-metal diffusions; time and temperature were the important variables. Since 1958 these dimensional controls have been maintained by photolithographic techniques and diffusion processes.

The use of the masks formed by the processes varies according to the fabrication procedure. Reproduction of any of the microelectronic circuits is not too dissimilar from the three color dye transfer processes for color photography; thus, in screen printing, dyes were replaced with cermets; in evaporation or sputtering printing, the gaseous vapors of metals replace the dyes; integrated circuits use an oxidizing vapor to form an oxide mask on the base material which in turn is employed as a mask for printing a metallic diffusion pattern in silicon. Indeed, these are all extensions of the printer's art united with basic concepts of molecular science and the controlled manipulation of electronic processes in materials.

Electronic Processes in Materials

The basic electronic phenomenon associated with microelectronics is conduction in metals, semiconductors, and insulators. The following electronic processes are available, but no practical technology of utilization in microelectronics exists.

Electronic Processes of Interest to Microelectronics

- Electron Conduction
  - Metals
    - Photoemission
  - Semi-Metals
  - Semiconductors
    - Photoconductivity
    - Photoelectricity
    - Peltier and Seebeck Effects
    - Hall Effect
    - Thermisters
    - Superconductors
  - Photoemission

Dielectric

Piezoelectricity

Ferroelectricity

Ionic Conductivity

Magnetic

Ferromagnetism

Ferromagnetic Resonance

Paramagnetic Resonance

Cyclotron Resonance

Stimulated Emission of Electromagnetic Radiation

Lasers

Masers

Conduction processes can best be characterized by the behavior of energy bands and the allowed energy states of electrons in crystals. This is illustrated in figure 2. In metals, electrons freely enter the highest allowed band as it may not be filled; in semiconductors, the highest allowed energy band may be filled and the energy gap is of sufficient magnitude to be crossed by thermally excited electrons; for insulators, it may be filled and separated from the next allowed band by a wide forbidden gap. Conduction phenomena in insulators yield dielectrics whose processes are normal, or linear, as with silicon dioxide, or nonlinear as illustrated by the ferroelectrics. Resistors are derived by conductive processes and may be metallic thin films, ohmic normal metals as thick films, metal-metal oxides dispersed in an insulating matrix as in cermets, or minority carrier concentration in a semiconductor crystal. Active elements such as transistors are based primarily on semiconductor processes and silicon is the predominant base material with boron and phosphorous as the significant dopants. Except for highly specialized applications, silicon semiconductor processes apparently satisfy virtually all of the material requirements of microelectronics and P-N junction theory the academic requirements.

Before leaving this brief materials discussion I want to state that fundamental research has yielded these fruits to the engineer. Electronic processes in materials are the essence of microelectronics and we are heavily dependent on existing and future basic research efforts directed towards a better understanding of these processes or the revelation of new processes. We must look to new technologies required to utilize these phenomena. In the case of the transistor, it was not until planar diffusion techniques were developed that predictable performance and reliability became possible.

Microelectronic Systems

Semiconductor integrated circuit digital functions became commercially available in 1960. Shortly thereafter linear integrated circuits were developed. A wide variety of functions are available. These include low-level differential amplifiers, biomedical signal conditioners, operational amplifiers, and oscillators. The most recent developments include low-level high-impedance amplifiers suitable for use in biomedical experiments. Growth was phenomenal and early prognostications of slow acceptance of microelectronic integrated circuits were completely shattered in 1964 with mass acceptance of microelectronics. Those of us associated with spacecraft instrumentation logically were drawn to microelectronics. Potential reliability, so necessary for spacecraft and the reduction of weight and size stimulated our interest and in 1962 NASA initiated research and development programs intended to implement microelectronics into spacecraft instrumentation. Government support of research in this area was extensive prior to 1962 and industry was diligent in supporting much of their own research and development, but the development was computer oriented. Power-consuming digital functions could not be employed in spacecraft and amplifiers for biomedical experiments were not available. Initially, the introduction of microelectronics into spacecraft was slow and deliberate as the reliability inherent to the discipline had not been experimentally established. But the spacecraft instrumentation specialist had to test and verify reliability predictions. As a result of these tests electronics will find wider usage in spacecraft. The potentials can best be illustrated by considering a deep space mission to the planet Jupiter.[11] A nominal thrust mission would take approximately 20,000 hours. In figure 3 I have shown that conventional components, even with redundant circuitry, could not successfully support such a mission. However, by 1967 or 1968, the reliability of microelectronic functions will have been established at a value where such a mission could be executed with a 90-percent chance of success. In addition, as probe distances increase, communication of command and telemetry information becomes increasingly restricted. The power required to transmit data from a space vehicle to earth tracking stations increases as the amount of information to be transmitted in a unit time is increased. For deep space probes, the power requirements become staggering unless data transmission rates are reduced; as a consequence, onboard data processing sampling and storage must be extensive. Within the constraints of existing spacecraft this can only be achieved with microelectronics.

An excellent example of what can be achieved with microelectronics is shown in figure 4. This is a six-channel pulse coded telemetry system weighing 6 ounces. The transmitter is not shown, nor is the weight included. Its advantage of weight and size is obvious. The most interesting aspect of this system is the portability and applicability as a mobile biomedical data system. The six channels could process EKG, respiration, and temperature data and is small enough to be carried by a patient or by roaming animals. The power requirements would be dictated by the communication distance which in a laboratory could be very short. Here, I believe, is one of the most attractive applications of microelectronics. Cathode follower equivalents can now be innocuously placed in or on the biomedical subject with a decrease in threshold noise and an increase in sensitivity. Biomedical instrumentation and experiments can assume a new order of complexity and neuron synthesis of a complex nature can be constructed and reconstructed for better modeling. Many devices are available at this time and the biomedical instrumentation specialist should eventually become familiar with this new discipline for they affect concepts of electronic modeling of biomedical functions, prosthetics, and experimental instrumentation.

Conclusion

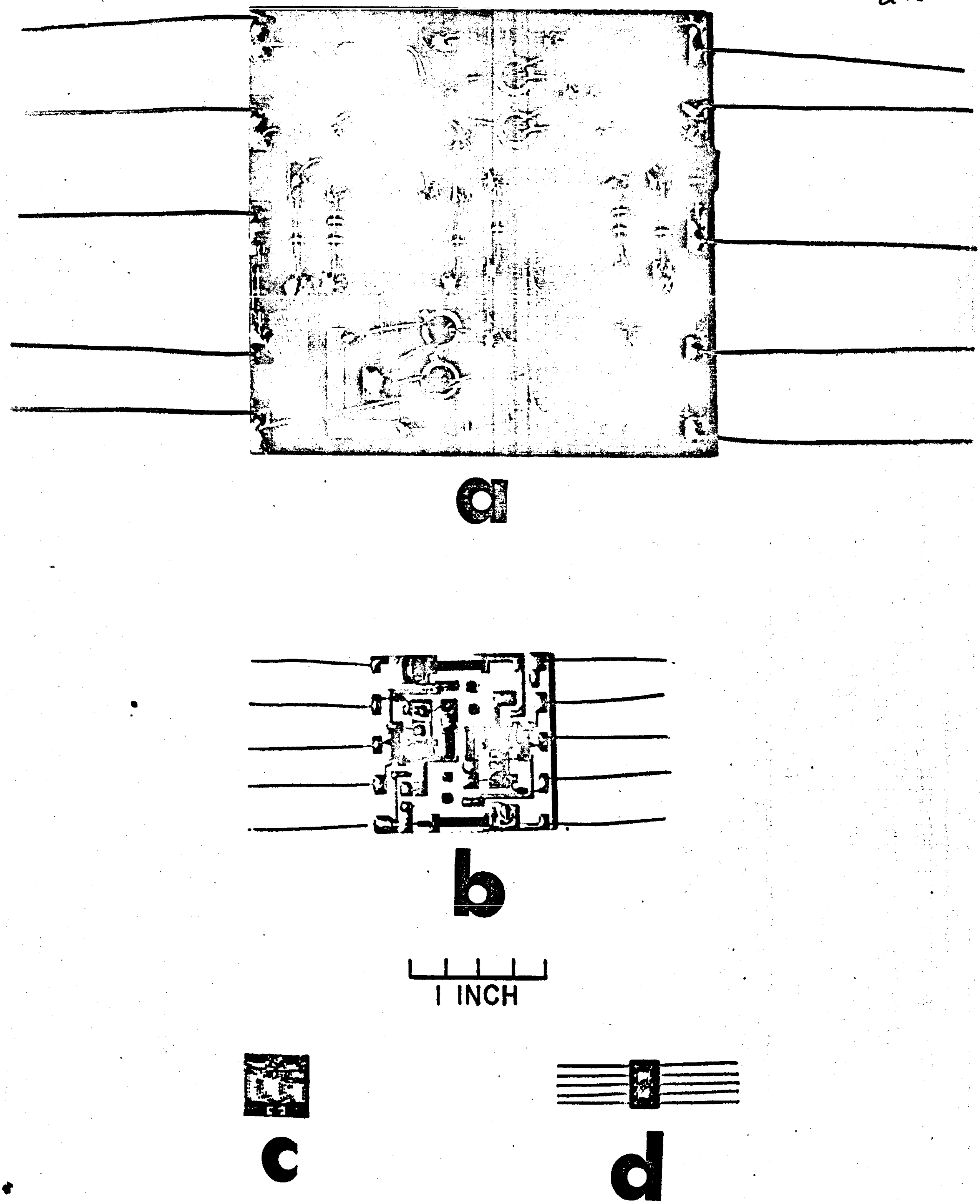
I began by discussing microelectronics. I cannot, in my own mind, however, restrict my thoughts solely to electronic functions, reliability, or spacecraft. Out of today's potpourri of technologies has evolved a discipline called microelectronics. In part, it is a sophisticated method of microminiaturization, but primarily it is a philosophy. This is unique in electronics inasmuch as one of the early triumps of microelectronics has been an acceptance of electronics as a singular, rather than a more convenient or economical solution to problems of instrumentation. The economic advantages of microelectronics should, however, make available to small research laboratories highly specialized computers and instrumentation which hitherto have been considered impractical or costly to the biologist. Subcutaneous implantation of electronics systems can more realistically be approached with the availability of versatile and reliable electronic functions and the insertion of controlling electronic functions into the closed electrical loop of a living system can also be accomplished.

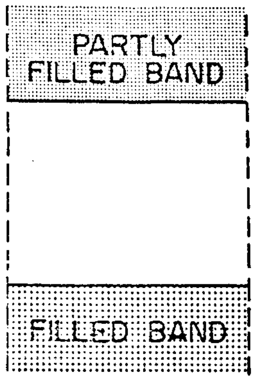
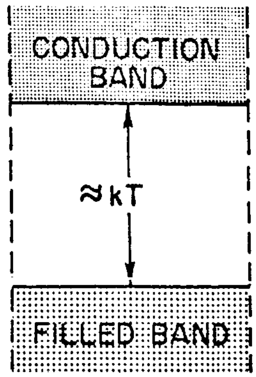
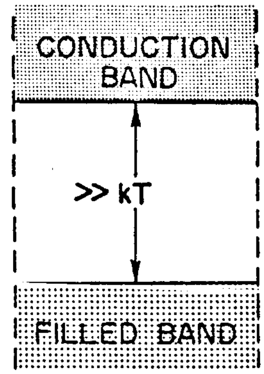
The ability to make decisions and conceive ideas is relinquished by man only in a small part to devices with speed and assisted sensory capacity. The conceptual mechanism and most of the decisions have been retained because the machines are inadequate. The adaptation of man over several decades cannot be progamed into a machine in one decade. However, due to technological and fundamental research, we are converging on solutions to microadaptation functions. Crude machines today are giving us the rules of adaptation on a small scale and microelectronics is contributing to smaller and reliable functions. For the first time, it appears that electronics may evolve as a major weapon in attacking socio-psychological and physiological problems, through adaptive machines and electronic prosthesis. Electronics, to date, has served to extend our senses, speed our computations, and nothing more; it has served to unite poorly connected environments and yet by its very nature is richly connected to environments of interest. If we conceive of men as adaptive mechanisms, every cell modification contributing to its share of knowledge, acquired through known or unknown senses, giving us physical and mental responses to our environment, can we not synthesize a small part of that adaptation and by so doing inquire into the depth of cell adaptation, of virus and virus growth, behavioral patterns, and virtually all of those processes associated with man. To my knowledge this approach to the task has not begun. Learning machines, in a primitive state today, joined by molecular electronics and all the tools of molecular engineering are the first step in this direction.

References

1. C. Brunetti and R. W. Curtis, "Printed Circuit Techniques," NBS Circular 468, November 15, 1947.
2. T. A. Prugh, J. R. Nall, and N. J. Doctor, "The DOFL Microelectronics Program," Proceedings of the IRE, Vol. 47, pp. 882-894, May 1959.
3. J. Bardeen and W. H. Brattain, "The Transistor, a Semiconductor Triode," Phys. Rev. Vol. 74, pp. 230-231, July 15, 1948.
4. W. Shockley, "The Theory of P-n Junctions in Semiconductors and the p-n Junction Transistor," Bell Sys. Tech. J., Vol. 28, pp. 435-489, July 1949.
5. A. B. Phillips, "Transistor Engineering," McGraw-Hill Book Company, Inc., New York, 1962.
6. G. Strull, "A Light Telemetry System," 1959 National Electronics Conference, October 1959.
7. K. R. Shoulders, "Research in Microelectronics Using Electron-Beam-Activated Machining Techniques," PB 171027, Office of Technical Services, U.S. Department of Commerce, September 1960.
8. P. R. Low, et al., "Components for Trainable Systems," Digest of technical papers, 1962 International Solid State Conference, Phila., Pa.
9. "Photosensitive Resists for Industry," Kodak Industrial Data Book, P-7, 1962.
10. "Fired on Resistors," E. I. Dupont Electrochemical Bulletin A-29656, 1963.
11. C. Husson, "Bringing Microelectronics to Spacecraft," Astronautics and Aeronautics Vol. 2, No. 4, pp. 29-33, April 1964.

List of Figures and Table


a
b
1 INCH
c
d

		
Conductivity related to the mobility of the charged carriers as the electrons freely cross the energy gap.	Conductivity related to the external excitation of electrons to cross the energy gap.	No crossing of the energy gap. Electric field excitation yields a bound charge which acts as a dielectric and hence a capacitor.
Free electron conduction	Valence electron conduction	Ion conduction
$R = Ae^{\frac{E_g}{kT}}$	$R = Ae^{-\frac{E_g}{kT}}$	$R = Ae^{-\frac{E_g}{kT}}$ (Ion conduction)

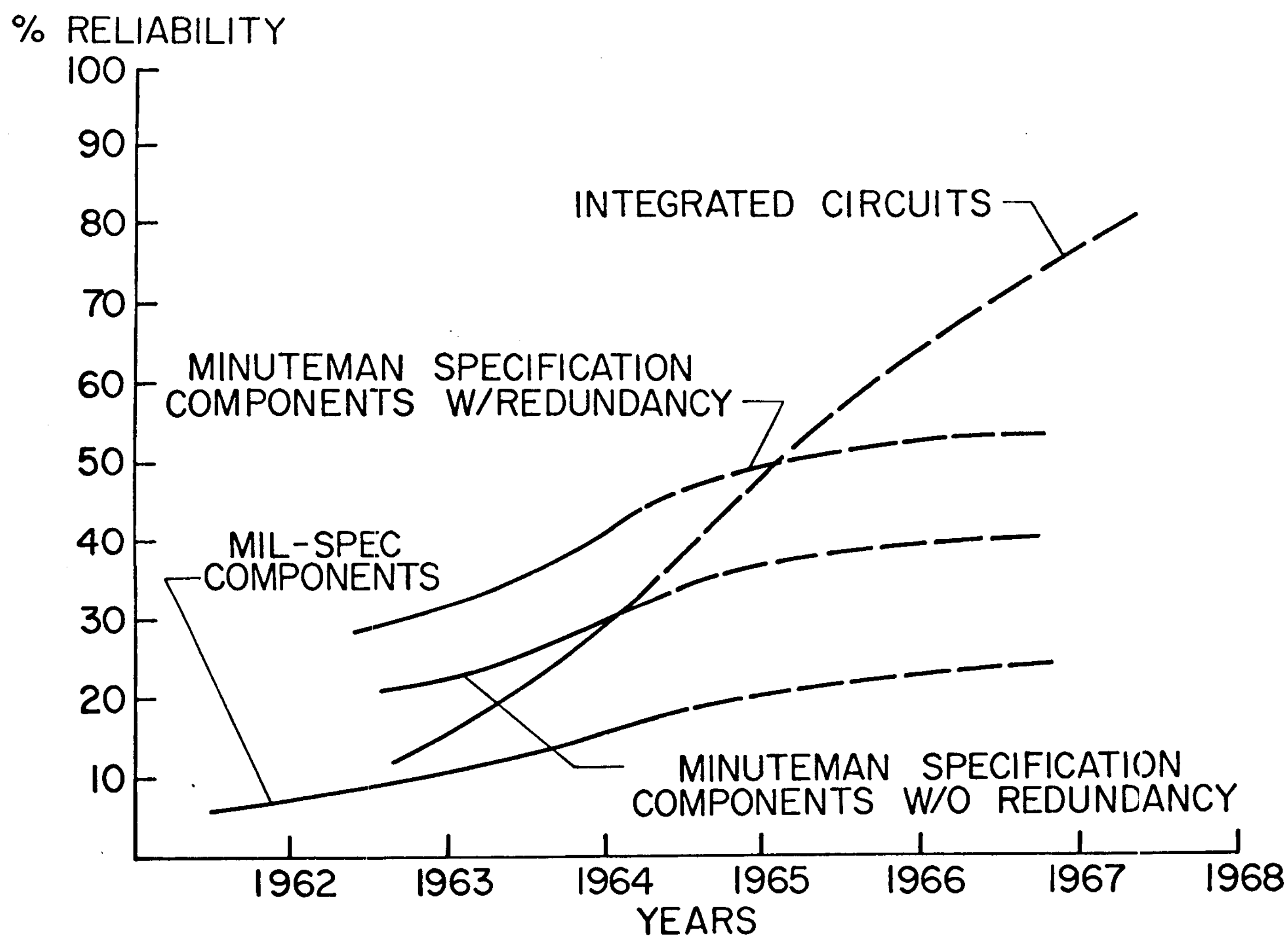
R = Resistance

k = Boltzmann constant

T = Temperature

E_g = Energy gap

A = Constant



% RELIABILITY
100
90
80
70
60
50
40
30
20
10
1962
1963
1964
1965
1966
1967
1968
YEARS
INTEGRATED CIRCUITS
MINUTEMAN SPECIFICATION COMPONENTS W/REDUNDANCY
MIL-SPEC COMPONENTS
MINUTEMAN SPECIFICATION COMPONENTS W/O REDUNDANCY

NASA
L-65-2559

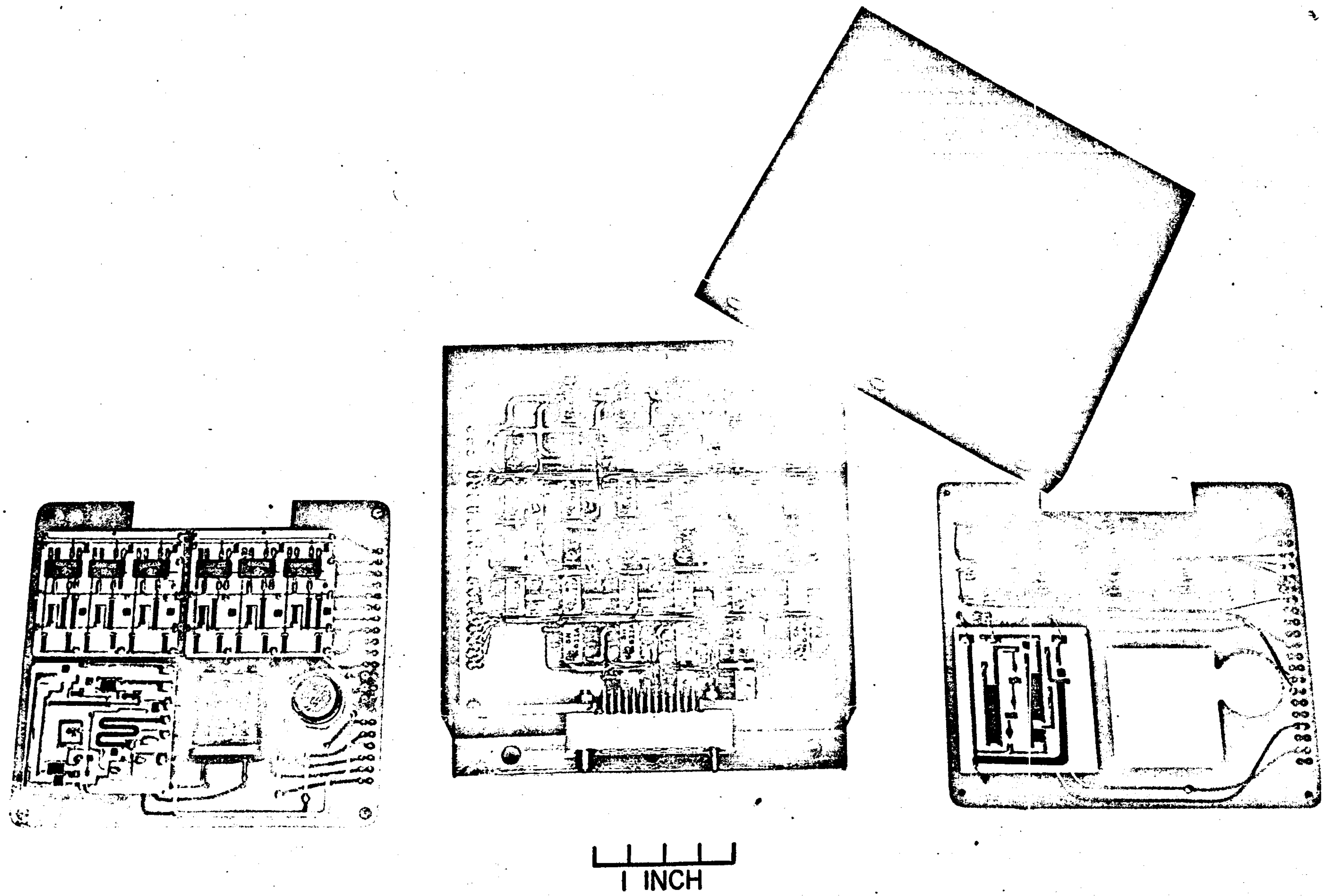


Table 1.- Evaluation of the Three Basic Microelectronic Techniques

Showing Areas of Advantageous Application

Factors considered	Techniques		
	Integrated circuits	Thin-film circuits	Thick-film hybrid circuits
Potential reliability	×		
Size	×		
Weight	×		
Interconnections	×		
Design flexibility			×
Circuit applicability			×
Radiation damage		×	
Cost - low quantity			×